

Modelling and optimisation of solar organic rankine cycle engines for reverse osmosis desalination

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Abstract

The objective of this paper is to model and optimise solar organic rankine cycle (ORC) engines for reverse osmosis (RO) desalination using currently available solar thermal collectors. The proposed systems are intended to be potentially attractive for remote areas without (or with very high cost) access to the public electricity grid.

In this study the ORC system is modelled using the Aspen Plus process simulator, with the required inputs from other programmes to model Reverse osmosis and thermal solar plants in the same modelling platform. The first part of this paper analyzes a comprehensive list of candidate working fluids for the ORC desalination application, and a selection is made of the most interesting fluids according to the type of solar collectors used in each case. The optimal operating temperature is calculated for the solar ORC integrated with the RO plant that optimises the global ORC-thermal solar plant efficiency. The second part of the paper deals with the applicability of the system obtained. Two case studies were examined from Almería and Barcelona that can be considered representative of two different levels of solar radiation characteristic of the Mediterranean area of Spain. In these case studies the area of the solar field collectors was calculated, considering both brackish and sea water desalting applications for a handling capacity of 15 m³/day. An economic estimation is also reported comparing the present results with those of an equivalent photovoltaic-RO plant. The technical-economic results obtained for the two locations suggested the adequate thermal solar technology to be that represented by the PTC collector system. The use of an equivalent photovoltaic system to generate electricity to drive the RO desalination system had a higher cost than the optimised solar ORC-RO system specially when using the best solar thermal technology.

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1. Background and objectives

The application of renewable energies such as solar energy to produce fresh water is receiving increased interest due to the need for solving the water shortage problems in various areas of the world at the same time as conventional energy sources used for obtaining water in different scenarios become depleted.

The use of renewable energy sources in water desalination is of interest, especially for remote areas where a conventional energy supply is not easily available. This

application is, however, still not well developed and it has only been tested in pilot plants and at a few demonstration sites. Numerous examples of research work on renewable energy desalination systems can be found in [1–4] as well as in other reviews in the literature. There are various desalination methods available on the market that use mainly thermal or mechanical energy in their fundamental separation processes. Among them, reverse osmosis (RO) is quite suitable for small to medium capacity systems and also has good perspectives for cost reduction and improvement in efficiency in the near future [5]. In RO, pressure applied to the saline solution forces pure water through a semipermeable membrane. The membrane is selective and allows the passage of water but is impermeable to other substances.

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Nomenclature

η_0	optical efficiency parameter for solar collectors	OM _{RO}	operation and maintenance cost of the RO (€/m ³ /day)
η_{CSP}	flat plate collector efficiency	OM _{solar}	operation and maintenance cost of the solar plant [€/m ²]
η_{ETC}	evacuated tube solar collector efficiency	ORC	organic rankine cycle
η_{FPC}	flat plate solar collector efficiency	P_1	inlet ORC turbine pressure (bar)
ρ_i	density of stream i (kg/m ³)	P_2	outlet ORC turbine pressure (bar)
η_{ORC}	net organic rankine cycle efficiency	P_c	fluid critical pressure (bar)
η_{PTC}	parabolic trough solar collector efficiency	PREHEAT	preheater heat exchanger
η_{solar}	thermal solar plant efficiency	PTC	solar parabolic trough collector
η_{total}	overall efficiency for the solar ORC system	Q_{ORC}	total thermal energy supplied to the ORC (kW)
A	aperture area of the solar collector field (m ²)	REGEN	regenerator heat exchanger
a_1	efficiency parameter for the FP, ET and compact PT collectors (W/m ² °C)	RO	reverse osmosis
a_{11}	efficiency parameter for the High-temperature PT collectors (°C ⁻¹)	SSAP	high pressure raw water stream
a_2	efficiency parameter for the FP, ET and compact PT collectors (W/m ² °C ²)	SSBP	low pressure raw water stream
a_{21}	efficiency parameter for the high-temperature PT collectors (W/m ² °C)	SSBTP	raw water inlet
a_{31}	efficiency parameter for the high-temperature PT collectors (W ² /m ² °C ²)	SSMP	medium pressure raw water stream
C_{ORC}	total cost of the ORC (€)	SUPHEAT	superheater heat exchanger
C_{RO}	total cost of the RO plant (€)	T_1	highest temperature in the ORC, turbine inlet temperature (°C)
C_{solar}	total cost of the solar plant (€)	T_a	ambient temperature (°C)
c_{tot}	annualised specific cost of the solar ORC–RO system (€/m ³)	T_c	critical fluid temperature (°C)
DAP	brine discharge at high pressure	TDS	total dissolved solids (ppm or mg/l)
DBP	brine discharge at low pressure	T_f	fluid temperature at the solar collector outlet (°C)
ETC	solar evacuated tube collector	w_{cons}	specific ORC capacity per flow of desalted water (kW/m ³ /day)
EVAP	evaporator heat exchanger	W_{net}	net power produced by the ORC cycle (kW)
f	capital recovery factor (y ⁻¹)	W_{ORCp}	power of the ORC circulation pump (kW)
FPC	solar flat plate collector	W_{Peak}	peak power delivered by the photovoltaic system (kW)
IC _{RO}	investment cost of the RO plant (€)	W_{PV}	power delivered by the photovoltaic system (kW)
IC _{solar}	investment cost of the solar plant (€)	W_{rec}	mechanical power recovered in the RO system (kW)
I_{solar}	solar radiation (global or direct radiation depending on the type of collector) (W/m ²)	W_{RO}	power of the high-pressure RO pump (kW)
m_{desal}	desalinated water mass flow rate (kg/s)	W_{solarp}	power of the solar plant circulation pump (kW)
$m_{\text{ORC,br}}$	ORC working fluid mass flow for brackish water desalination (kg/s)	W_{turb}	ORC turbine power (kW)
$m_{\text{ORC,sw}}$	ORC working fluid mass flow for seawater desalination (kg/s)	$w_{\text{turb,br}}$	specific ORC capacity for brackish water desalination (kJ/kg)
m_{solar}	mass flow rate of the solar primary circuit (kg/s)	$w_{\text{turb,sw}}$	specific ORC capacity for seawater desalination (kJ/kg)

The energy to produce the required pressure for RO can be generated with renewable energy sources such as wind energy, dish-stirling systems, solar thermoelectrical plants or photovoltaic solar electrical generation. Solar thermal energy coupled to a power cycle by using direct mechanical power can also be employed.

Water is commonly used in rankine power cycles, although other types of inorganic (ammonia, ammonia/water, ...) and organic fluids (hydrocarbons, fluorocarbons, siloxanes, ...) can be used. The main advantage of organic working fluids in rankine cycles is that they can

be driven at lower temperatures than similar cycles using water and also in many cases superheating is not necessary. This results in a practical increase in efficiency with respect to the use of the cycle with water as the working fluid. Another option is to use advanced steam reciprocating engines as expanders that claim higher efficiency (30% at a temperature of 400 °C) than rankine cycles [6] but this technology is less developed and will not be considered in the present study.

The research on ORC has been focused in the production of electricity, mainly related to recovery of low tem-

perature waste heat, geothermal heat, biomass, or solar energy. Many references to these applications are available in the literature. A couple of facilities with ORC plants using solar thermal energy were constructed in 1978 in Cadarache, France and in 1981 at El Hamrawin, Egypt, but unfortunately there has been little information published about them [7]. A commercial parabolic trough ORC power plant completed in 2006 in Arizona is of particular interest. It is a 1 MWe plant using *n*-pentane as the working fluid for the ORC, and is based on plants used in geothermal applications having 10,340 m² of parabolic trough collectors [8]. Studies on ORC applications for desalination are very scarce although a few projects exist and some studies are available. The Vari-Power company, based in California, started to develop an RO-based desalination system driven by solar thermal energy [9,10]. A patented direct drive engine (DDE) converts heat to the hydraulic power required by the RO. To our present knowledge, this project is still in the pilot stage. In [11] it is proposed a solar ORC system using R-134a and evacuated tube collectors. The system efficiency is low (7%) but the authors considered it comparable to equivalent photovoltaic desalination systems. The first laboratory test simulating the heat provided by solar collectors has been given by Manolakos et al. [12]. Burgess and Lovegrove [13] discussed the application of solar thermal powered desalination using membrane and distillation technologies. One of their conclusions was that more detailed analyses of solar driven RO are required to determine its costs and applicability. In summary, existing research on solar ORC for desalination is very limited, and few efforts have been reported on determining the most useful working fluids for this application.

The objective of this paper is to model and optimise solar ORC engines for reverse osmosis desalination using currently available solar thermal collectors to drive the ORC. The system is intended to be potentially attractive for use in remote areas without (or with very high cost) access to a public electricity grid. This work is part of the OSMOSOL research project carried out by the University of La Laguna (Tenerife, Spain), CIEMAT-Plataforma Solar de Almería, (Almería, Spain) and Universitat Rovira i Virgili. It is funded by the Spanish government and is devoted to the development of solar ORC technology for desalination [7].

The first part of the following section describes how the entire system is modelled, and then a first screening of working fluids is described. We then calculate the optimal operating temperature of the solar ORC integrated with the RO plant that optimises the overall ORC-thermal solar plant efficiency. Finally, the proposed system is applied in two case studies in two different locations for production of 15 m³/day of fresh water using seawater or brackish water as inputs.

2. Description of the system, modelling and optimisation procedure

The system consists of three main subsystems: the ORC, RO and solar plants. The organic rankine subsystem is a thermodynamic power cycle that uses an organic working fluid instead of water and is known to yield excellent performance at temperatures up to about 400 °C. The working fluid is heated to boiling, and the expanding vapour is used to drive a turbine and more generally any expander (Fig. 1). This expander provides all the mechanical energy required to drive the high-pressure RO pump and the high

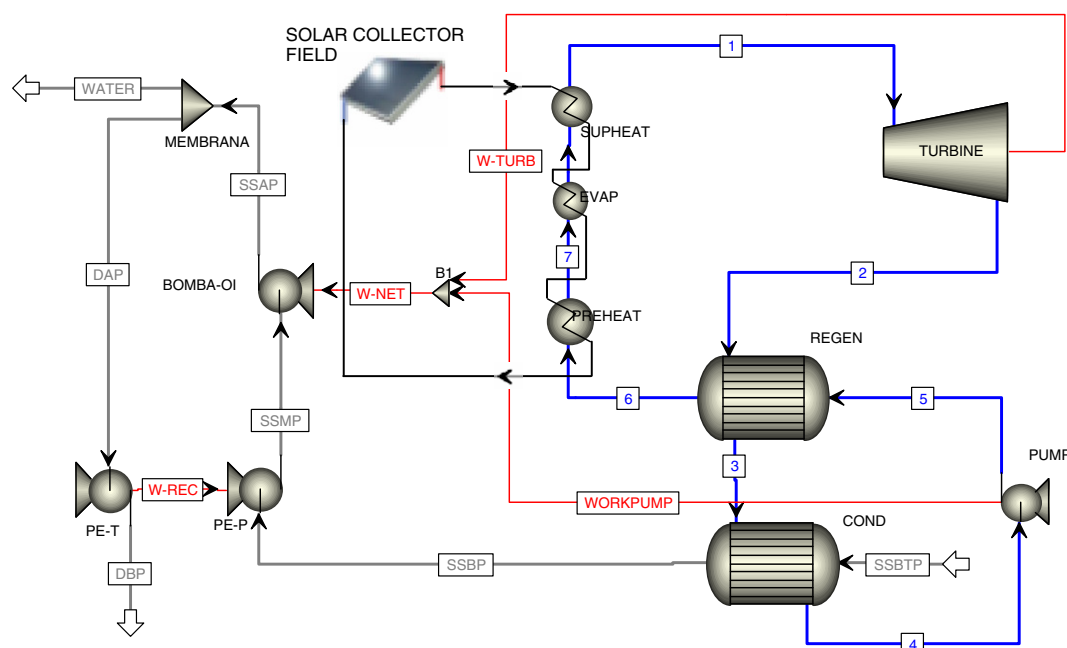


Fig. 1. An integrated ORC–RO plant modelled with Aspen Plus.

pressure ORC and solar plant circulation pumps Eq. (1). In more conventional applications the work is commonly used to drive an electric generator.

$$W_{\text{turb}} + W_{\text{rec}} = W_{\text{RO}} + W_{\text{ORCp}} + W_{\text{solarp}} \quad (1)$$

In this process, after its expansion, the working fluid vapour is condensed back into the liquid state using the raw water feed for the desalination subsystem as a coolant. This water is in turn preheated to increase the performance of the RO (Fig. 1). The condensed working fluid is recycled back through the system to again produce work. As will be explained later a regenerator is included to increase energy efficiency. The heat required to preheat, evaporate and superheat the working fluid is obtained in this case from a thermal solar plant using water or thermal oil as a heat transfer fluid, depending on the working conditions as described below.

In this study the ORC system is modelled using the process simulator Aspen Plus [14] with the required inputs from other programmes in order to model the reverse osmosis and the thermal solar plant in the same modelling platform. The TRNSYS simulation environment for thermal systems [15] was selected to model the thermal solar plant and calculate the required thermal solar collector field based on its completeness regarding meteorological and solar plant component libraries.

There are some computer programmes for calculation of the performance of RO systems using different commercially available membranes such as winflows from osmonics membranes or IMSDesign from hydranautics membranes among others. In this study the ROSA Software [16] based on Dow membranes is used to provide the required input

parameters necessary to build the RO subsystem model in Aspen Plus.

The modelling of the ORC, RO and solar plant subsystems are described in Sections 2.1–2.4 below. In a subsequent Section 3 a first selection of working fluids is made including the selection of the operating pressure at the inlet of the turbine and at the condenser. In a following step (Section 4), the pressures are kept constant at the optimum values found in the first step and the turbine inlet temperature is optimised as a compromise between high ORC cycle efficiency and solar plant efficiency that decreases as this temperature increases (Fig. 2). The optimal operating temperature of the solar ORC system is then found using the *Optimiser* function of Aspen Plus. The mass flow rate with each working fluid will also be one output of this optimisation model.

2.1. Organic rankine cycle

Aspen plus [14] was used to model the ORC integrated with the RO and solar plant subsystems (Fig. 1). The thermodynamic properties of all the fluids were calculated by means of the Peng–Robinson equation of state. The efficiency of the ORC was determined following Eq. (2), neglecting the power consumption of the solar plant circulation pump. The input parameters used in the model are given in Table 1. In this table the stream numbers and nomenclature refer to that of Fig. 1. To obtain the optimum operating pressures and to make a first selection of fluids, the ORC was modelled as a saturated cycle and as a superheated cycle to obtain the maximum capacity

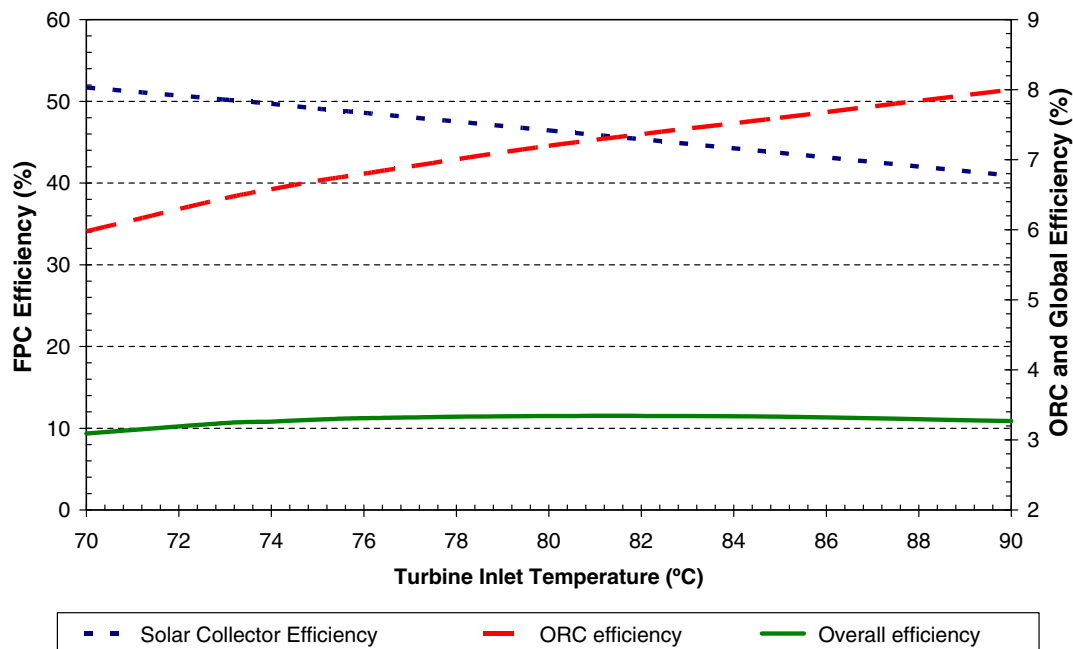


Fig. 2. Thermal solar plant and ORC efficiencies as a function of operating temperature in the ORC. Example for a superheating ORC using octafluoropropane and FP collectors.

Table 1
Input parameters used in the ORC–RO model

Equipment or stream	Parameter	Value
Turbine	Discharge pressure	P_2
	Isentropic efficiency	0.8
Regenerator (REGEN)	Quality outlet (str. 3)	1 (saturated vapour)
	Outlet temp. (str. 4)	5 (°C) subcooling
Condenser (COND)	Discharge pressure (str. 5)	P_1
ORC pump	Efficiency	0.8
	Pressure	P_1
Preheater (PREHEAT)	Quality outlet (str. 7)	0 (saturated liquid)
	Pressure	P_1
Evaporator (EVAP)	Quality outlet	1 (saturated vapour)
	Discharge pressure	22.4 (bar) (brackish water) ^a
RO pump		64.8 (bar) (sea water) ^a
	Efficiency	0.8
RO membrane	Recovery ratio (RR)	0.75 (brackish water) ^a
		0.5 (sea water) ^a
Pressure exchanger (RO energy recovery)	Pressure discharge	1 (bar)
	Pump efficiency	1
Turbine inlet (Str. 1)	Expander efficiency	0.98
	Pressure	P_1
Raw water inlet (Str. SS-BPT)	Quality	1 (saturated vapour)
	Flow rate	m_{ORC}
	Pressure	1 (bar)
	Temperature	15 (°C)
	Flow rate	5.29 (kg/s) (brackish water)
		7.94 (kg/s) (sea water)

^a Parameters calculated using the ROSA software.

$$\eta_{\text{ORC}} = \frac{W_{\text{net}}}{Q_{\text{ORC}}} = \frac{W_{\text{turb}} - W_{\text{ORCp}}}{Q_{\text{ORC}}} \quad (2)$$

2.2. Reverse osmosis system

The reverse osmosis requirements depend strongly on the characteristics of the raw water used. The salinity of water is usually expressed in terms of its total dissolved solids (TDS). The TDS include inorganic salts (principally calcium, magnesium, potassium, sodium, bicarbonates, chlorides and sulfates) and small amounts of dissolved organic matter. Sea water typically has a TDS of more than 25,000 mg/l. Water is considered brackish when its TDS concentration is between 1000 and 10,000 mg/l. According to the World Health Organisation (WHO) the palatability of water is considered to be generally good at a TDS level of less than 600 mg/l; drinking-water becomes significantly and increasingly unpalatable at TDS levels greater than about 1000 mg/l [17].

For the present study the TDS content of brackish water has been assumed to be 3000 ppm and 36,000 ppm for seawater as indicated in Hublitz et al. [18]. The RO system has been modelled with ROSA using case 2 modules connected in series with six membrane elements BW30-365 each for the brackish water. In the case of seawater, the configura-

tion consists of three modules connected in series with six membrane elements SW30HR in each one. The results obtained with ROSA were introduced as input parameters into Aspen Plus to model the integrated ORC–RO system. The RO membrane is modelled in Aspen Plus using the Recovery Ratio (RR) defined as the ratio between the flow rate of desalted water and the raw water at the inlet. This ratio is obtained by using ROSA introduced to the Aspen Plus model. Another important variable is the required pressure for the RO pump. All these parameters have been included in Table 1.

2.3. Thermal solar plant

The input parameters required for Aspen Plus to integrate the solar collectors subsystem into the integrated ORC–RO system were obtained by modelling this subsystem with the TRNSYS software.

It is not the purpose of the present work to review all the possible types of solar thermal collectors that could be coupled to ORC systems. Reviews of this kind, including collectors for medium to large electricity production plants and suitable for ORC applications can be found in the literature, for example that of Mills [19]. Some progress has been made in this area, including the compact PTC [20] or the new roof-integrated solar thermal energy collectors that claim to produce heated fluids at temperatures up to 400 °C for use in building energy systems [21]. These collectors use fixed special curved reflectors and a linear thermal receiver incorporating a secondary reflector which tracks the sun.

In the present analysis for ORC desalination the criterion used for choosing the appropriate type of solar collector includes whether they are easily available commercially or at least at an advanced stage of development. To reduce the number of cases to study, only one flat plate collector (FPC) and evacuated tube collector (ETC) were considered. For PTC two different types of collectors are considered due to the considerable difference between the new compact systems for medium-high temperatures and the collectors usually used for high temperatures in thermo-electrical solar plants.

The solar collector aperture area (A) for each ORC–RO system is a function of the local solar irradiation. The power required for brackish and seawater desalination and the efficiencies of the solar and ORC plant as shown in Eq. (3).

$$A = \frac{W_{\text{net}}}{I_{\text{solar}} \cdot \eta_{\text{ORC}} \cdot \eta_{\text{solar}}} \quad (3)$$

The product of solar and ORC plant efficiencies, referred to as overall efficiency, minimises the required solar collector area.

The solar collector instantaneous efficiency can be determined from the characteristic curve using the solar irradiance, mean collector and ambient temperature. The curve used for flat plate, evacuated tube and compact parabolic

trough collectors is expressed as shown in Eq. (4) and using the parameters given in Table 2 [21–23].

$$\eta_{\text{solar}} = \eta_0 - a_1 \cdot \left(\frac{T_f - T_a}{I_{\text{solar}}} \right) - a_2 \cdot \left(\frac{T_f - T_a}{I_{\text{solar}}} \right)^2 \cdot I_{\text{solar}} \quad (4)$$

The corresponding efficiency equation for the medium-high temperature parabolic trough collectors (PTC) is given in Eq. (5) [24]. The parameters are shown in Table 3.

$$\eta_{\text{solar}} = \eta_0 - a_1 \cdot (T_f - T_a) - a_2 \cdot \left(\frac{T_f - T_a}{I_{\text{solar}}} \right) - a_3 \cdot \left(\frac{T_f - T_a}{I_{\text{solar}}} \right)^2 \quad (5)$$

in the case of flat plate and evacuated tubes solar collectors I_{solar} corresponds to global solar radiation and in the case of parabolic trough collectors it corresponds to direct solar radiation.

Fig. 3 shows a screen shoot of the TRNSYS model used, which in this case is a ETC solar plant. The cases using other collectors are the same except for replacing the type of collector module and the performance parameters for the new ones. The TRNSYS modules used (Fig. 3) are the following:

- **Meteo**: meteorological data depending on the geographical location.
- **Radiation processor**: reads the irradiation of the climate data file and sends it to the collector block bearing in mind the position and the angle of the collector.
- **Collector**: models the solar collector field (type of collectors, efficiency parameters, etc).
- **Collector irradi**: calculates total irradiation depending on the day and the place studied.
- **Irrad control and flow rate control**: these are controllers that manipulate the flow rate through the solar field receiving the signal of radiation and the outlet temperature of the solar thermal collector.
- **Pump**: it is a variable flow pump to change the flow rate through the solar field in order to keep the temperature constant at the solar collector outlet.

Table 2
Efficiency parameters for FP, ET and compact PT solar collectors

	Flat plate collector (Sonnenkraft SK500)	Evacuated tube – CPC collector (Sydney SK-6)	Compact parabolic trough collector (Solitem PTC 1000)
η_0	0.768	0.665	0.75
$a_1 \left[\frac{\text{W}}{\text{m}^2 \cdot ^\circ\text{C}} \right]$	2.9	0.59	0.11232
$a_2 \left[\frac{\text{W}}{\text{m}^2 \cdot ^\circ\text{C}^2} \right]$	0.0108	0.0019	0.00128
Aperture area (m^2)	2.307	1.088	2.00

Table 3
High-temperature PTC (Eurotrough) efficiency parameters for Eq. (5)

Parameter	Value
η_0	0.75
$a_{11} [1/^\circ\text{C}]$	4.5×10^{-6}
$a_{21} \left[\frac{\text{W}}{\text{m}^2 \cdot ^\circ\text{C}} \right]$	0.039
$a_{31} \left[\frac{\text{W}^2}{\text{m}^2 \cdot ^\circ\text{C}^2} \right]$	3×10^{-4}

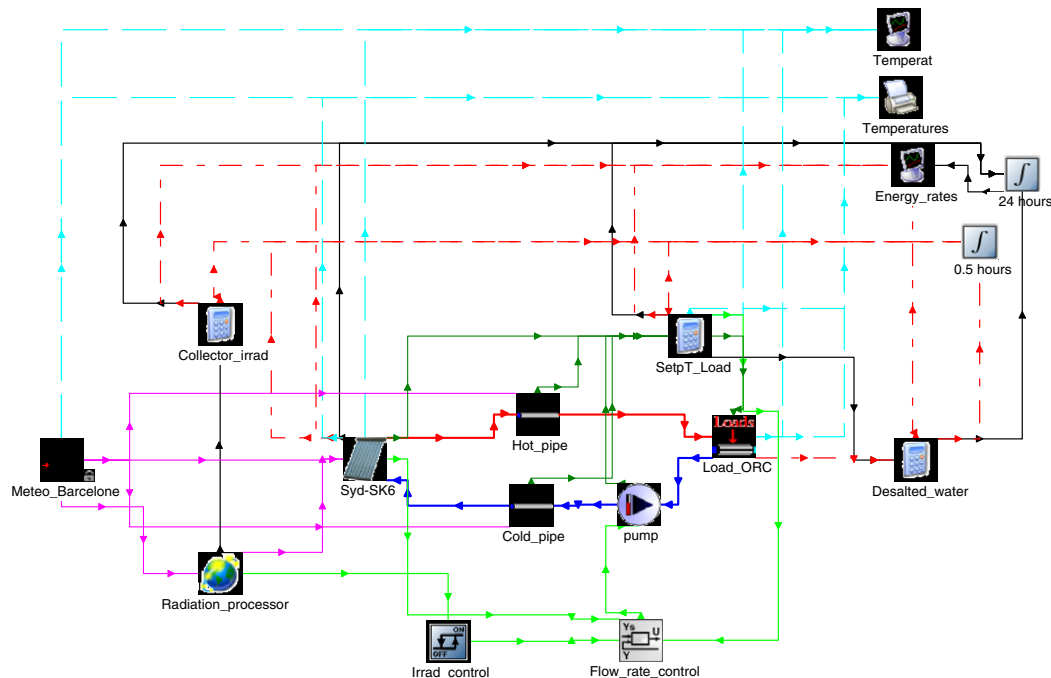


Fig. 3. TRNSYS model for the case of the ETC solar plant.

- SetT_{load}: this block monitors the temperature of the solar system pipes and when it exceeds a given set value the pump starts working. It also integrates the total heat transferred to the ORC plant when radiation is accumulated.
- Desalted water: this block calculates the flow rate of desalted water as a function of the flow rate of working fluid in the ORC.
- Integrators 0.5 and 24 h: definition of the simulation integration period.

2.4. Photovoltaic solar plant

Using TRNSYS we also modelled the solar production of electricity with photovoltaic modules to drive the high-pressure pump of the RO system in order to compare it with the performance of the proposed solar ORC for RO desalination. The TRNSYS modules used for the solar PV plant are the following:

- Collector irradi., radiation processor and desalted water: the same modules as in the thermal solar plant modelling.
- T_a : converts ambient temperature from °C to K
- Type94a: models the photovoltaic array according to the parameters of the photovoltaic panel considered and the values of ambient temperature and solar irradiation. Type 94 employs a “four-parameter” equivalent circuit. The values of these parameters (not to be confused with formal component PARAMETERS in TRNSYS) cannot be obtained directly from manufacturers’ catalogs. However, Type 94 will automatically calculate them from available data.
- Type48a: models an inverter which transforms the direct current of the photovoltaic array into alternating current with an efficiency of 0.95. This alternating current is then used by the electrical motor which drives the high-pressure pump of the RO system.

The parameters used to model the PV module are based on the panel commercialised by Isofoton model IS-200/32 of 200 Wp per module. It uses monocrystalline solar cells, textured and with a reflection suppressing layer.

3. Preliminary selection of working fluids

In ORC applications, the choice of working fluid is critical since the fluid must have not only thermophysical properties that match the application but also adequate chemical stability at the desired working temperature. Andersen and Bruno [25] presented a method that allows the determination of the decomposition reaction rate constant of simple fluids at the temperature and pressure of interest. Results show that the thermal stability decreases in the following order: *n*-pentane>2-methylbutane>2,2-dimethylpropane and benzene>toluene.

Mixtures of fluids have not been explored at the present stage of work. Although with some mixtures condensation

and vapourisation processes may match better with the cooling and heating media reported in some previous studies using pure and siloxane mixtures, the benefits do not translate to better net power output [26].

Aspen Plus has a comprehensive library of fluids that can be used for ORC. Initially the working fluids considered can be linear, branched and cyclic hydrocarbons, refrigerants and siloxanes. From this initial list of potential working fluids, refrigerants containing chlorine were discarded because of their ban in relation to the ozone depletion problem. Fluids were also discarded which demonstrated an isentropic or a negative slope of the saturated vapour line in the Temperature–entropy diagram to reduce the need for superheating. Table 4 shows the final list of the working fluids selected with some of their relevant thermophysical properties.

A first group of simulations was made with the selected fluids to determine the best high pressure for the ORC using a saturated cycle configuration and for each working fluid. The simulation results of selected working fluids using the parameters shown in Table 1 at the points of Fig. 1 are presented in Table 5. The last two columns of this table represent the specific ORC power per unit of mass of working fluid.

Table 4
Preliminary selection of working fluids

Component name	Alt. name	P^a (bar)	P_c (bar)	T_c (°C)
Octafluoropropane	R-218	6.65	26.80	73.2
1,1,1,2-tetrafluoroethane	R-134a	4.88	40.56	101.1
1,1,1,2,3,3,3-heptafluoropropane	R-227	3.33	29.12	101.5
1,1,1,2,2-pentafluoropropane	R-245	3.39	31.37	107.0
Decafluorobutane	R-31(1B)	1.92	23.23	113.0
Octafluorocyclobutane	R-C318	2.24	27.78	114.0
1,1,2,2-tetrafluoroethane	R-134	3.96	46.40	118.7
Isobutane	R-600A	2.60	36.40	134.8
1,1,1,2,3,3,3-hexafluoropropane	R-236EA	1.43	34.12	139.4
Bis-difluoromethyl-ether	R-E134	1.44	42.28	147.0
<i>N</i> -butane	R-600	1.76	37.96	152.3
2-difluoromethoxy-1,1,1-trifluoro	R-E245	0.58	34.20	170.0
Ethyl-amine	R-631	0.94	56.20	183.3
Isopentane (2-methyl-butane)	–	0.64	33.70	187.2
Diethyl-ether	R-610	0.48	36.40	193.5
<i>N</i> -pentane	–	0.46	33.64	196.5
Dibromodifluoromethane	R-12B2	0.76	40.70	204.8
Methyl-formate	R-611	0.52	60.00	214.3
1,2-dibromotetrafluoroethane	R-114B2	0.30	33.93	215.0
<i>N</i> -hexane	–	0.13	30.58	234.7
Hexamethyldisiloxane	MM	3.43×10^{-2}	19.1	245.4
<i>N</i> -heptane	–	3.61×10^{-2}	27.27	267.0
Cyclohexane	–	8.19×10^{-2}	40.75	280.5
Octamethyltrisiloxane	MDM	2.86×10^{-3}	14.40	291.0
<i>N</i> -octane	–	1.04×10^{-2}	24.97	296.2
Toluene	–	2.23×10^{-2}	41.00	319.0
Decamethyltetrasiloxane	MD2M	3.08×10^{-4}	12.2	325.8
Dibromomethane	R-30B2	3.55×10^{-2}	71.7	337.8
Ethylbenzene	–	7.04×10^{-3}	36.10	344.0
<i>N</i> -propylbenzene	–	2.42×10^{-3}	32.00	365.0
<i>N</i> -butylbenzene	–	6.98×10^{-4}	28.90	388.0
Tribromomethane	R-20B3	3.97×10^{-3}	60.90	422.9

^a Vapour pressure at 15 °C, the expected condensing pressure for the ORC–RO system.

Table 5
Simulation results of the selected working fluids with a saturated cycle configuration

Working fluid	1		2		3	4	5	6	ρ_2 (kg/m ³)	η_{ORC} %	$m_{\text{ORC,br}}$ (kg/s)	$m_{\text{ORC,sw}}$ (kg/s)	$w_{\text{turb,br}}$ (kJ/kg)	$w_{\text{turb,sw}}$ (kJ/kg)
	T (°C)	P (bar)	T (°C)	P (bar)	T (°C)	T (°C)	T (°C)	T (°C)						
Octafluoropropane	68.6	25.0	32.7	10.0	29.9	24.9	26.8	29.0	98.23	4.60	1.92	6.012	6.25	4.66
1,1,1,2,3,3,3-heptafluoropropane	96.0	26.0	41.7	5.00	28.3	23.3	24.9	34.6	37.02	9.11	0.787	1.7	15.25	16.47
1,1,1,2,2-pentafluoropropane	101.0	28.0	38.9	5.00	27.8	22.8	24.7	32.7	29.36	10.23	0.617	1.429	19.45	19.59
Decafluorobutane	110.4	22.0	61.5	3.00	28.8	23.8	25.2	50.6	27.95	12.32	0.741	1.9289	16.19	14.52
Octafluorocyclobutane	109.7	25.0	52.9	3.00	33.2	28.2	29.8	48.0	32.22	11.53	0.601	1.48	19.97	18.92
1,1,2,2-tetrafluoroethane	107.6	38.0	28.7	6.00	28.0	23.0	25.0	25.5	27.59	11.58	0.399	0.9862	30.08	28.39
Isobutane	126.9	32.0	47.4	4.00	29.9	24.9	27.1	40.0	9.57	13.94	0.175	0.409	68.57	68.46
1,1,1,2,3,3-hexafluoropropane	132.2	30.0	58.6	3.00	36.4	31.4	33.0	48.8	17.76	13.67	0.349	1.8199	34.38	15.39
Bis-difluoromethyl-ether	136.6	35.0	44.1	3.00	35.6	30.6	32.3	37.9	14.39	13.19	0.303	0.741	39.60	37.79
<i>N</i> -butane	145.0	34.0	61.9	4.00	42.1	37.1	39.3	53.9	9.12	14.13	0.1606	0.402	74.72	69.65
2-difluoromethoxy-1,1,1-trifluoro	163.2	30.0	73.2	1.00	28.5	23.5	24.8	57.5	5.34	17.69	0.2299	0.5195	52.20	53.90
Ethyl-amine	161.8	40.0	35.0	2.00	34.7	29.7	31.4	31.6	3.68	16.00	0.0912	0.2282	131.58	122.70
Methyl-formate	168.9	30.0	32.2	1.00	31.1	26.1	27.2	27.9	2.42	19.06	0.1025	0.2458	117.07	113.91
Isopentane (2-methyl-butane)	178.5	30.0	86.8	1.00	26.8	21.8	23.4	70.3	2.47	27.20	0.0821	0.1905	146.16	146.98
Diethyl-ether	185.8	32.0	84.1	1.00	34.5	29.5	30.6	67.7	2.56	18.42	0.0951	0.2163	126.18	129.45
<i>N</i> -pentane	188.7	30.0	94.4	1.00	35.9	30.9	32.5	77.5	2.42	16.74	0.1017	0.0241	117.99	116.83
Dibromodifluoromethane	189.0	33.0	88.1	1.10	37.2	32.2	33.8	71.9	8.78	17.36	0.0999	0.2616	120.12	107.03
1,2-dibromotetrafluoroethane	206.0	30.0	101.2	1.00	46.7	41.7	43.0	84.9	8.56	19.98	0.4025	0.9635	29.81	29.06
<i>N</i> -hexane	229.0	28.0	127.7	0.30	34.4	29.4	30.6	105.1	0.78	29.82	0.0866	0.2059	138.57	135.99
Hexamethyldisiloxane	241.4	18.0	162.0	0.075	30.2	25.2	26.0	136.9	0.34	25.54	0.1274	0.2976	94.19	94.09
<i>N</i> -heptane	260.3	25.0	155.7	0.075	28.7	23.7	24.6	128.7	0.21	29.67	0.0728	0.1728	164.84	162.04
Cyclohexane	269.0	35.0	145.0	0.20	34.6	29.6	31.2	120.0	0.49	26.51	0.0694	0.1615	172.91	173.37
Octamethyltrisiloxane	284.2	13.0	224.7	0.075	74.1	69.1	69.7	199.3	0.43	25.64	0.099	0.392	121.21	71.43
<i>N</i> -octane	289.7	23.0	195.1	0.075	52.2	47.2	48.0	167.0	0.22	33.75	0.0909	0.2188	132.01	127.97
Toluene	308.4	35.0	156.8	0.075	39.5	34.5	35.6	125.6	0.19	29.43	0.0597	0.1419	201.01	197.32
Decamethyltetrasiloxane	318.8	11.0	271.4	0.075	110.8	105.8	106.4	246.5	0.52	23.54	0.1238	0.5723	96.93	48.93
Ethylbenzene	336.3	33.0	201.4	0.075	59.6	54.6	55.8	171.3	0.20	27.09	0.0646	0.1532	185.76	182.77
<i>N</i> -propylbenzene	356.7	29.0	240.8	0.075	79.1	74.1	75.0	209.9	0.21	29.77	0.0725	0.1716	165.52	163.17
<i>N</i> -butylbenzene	381.5	27.0	276.3	0.075	99.7	94.7	95.6	244.9	0.22	27.86	0.0764	0.1797	157.07	155.82
Tribromomethane	391.2	45.0	91.8	0.075	65.9	60.9	63.0	81.4	0.63	28.96	0.1706	0.4545	70.34	61.61

The highest ORC efficiencies are obtained with fluids having a high critical temperature. The problem with these fluids is that the condensing pressure is low and consequently their density at the turbine outlet after expansion is also quite low as shown in Table 5. So in practice these fluids would require large-volume equipment in their operation. Siloxanes are in the group of high efficiency and low vapour density fluids. These fluids are used mainly in commercial cogeneration applications, where the condensing pressure is considerably high, making it advantageous to produce heat in the condensing process at the expense of lower cycle efficiency. In Table 5 it is clearly seen that the cycle efficiency increases as the critical temperature and molecule complexity increases. But the low cycle pressure decreases also. Different groups of fluids can be recognised in this table; (A) fluids with an efficiency close to 30% with low cycle pressures under atmospheric pressure, such as the siloxane fluids, (B) fluids with atmospheric pressure at the condensing section and with an efficiency of around 20%, such as *n*-pentane and isopentane. Isopentane offers a good ORC efficiency as well as acceptable density and specific power capacity compared with other high efficiency fluids. Finally, (C) there is another group of fluids below *n*-butane working at high condensing pressures showing an efficiency lower than 15%.

4. Optimisation and performance analysis of the solar ORC engine

Although superheating of dry organic fluids is not required for operating the system without problems of high liquid content after expansion, superheating increases the cycle net power capacity. Thus in Section 4, superheated cycles will be simulated and the most appropriate fluid will be selected for each type of solar collector. As mentioned above, there is a tradeoff between the maximum operating temperature of the ORC and the solar plant operating temperature. Thus, there is an optimal operating temperature that will depend among other factors on the type or working fluid and the type of solar collector used as seen in Fig. 2. The optimal operating temperature of the solar ORC system has been found using the *Optimiser* function of Aspen Plus. In the followed approach the temperature at the outlet of the solar plant is taken as 7 °C over the maximum temperature of the ORC, the turbine inlet temperature. Also it is considered an average solar radiation and ambient temperature of 800 W/m² and 20 °C, respectively.

4.1. Flat plate collectors

Based on the preliminary list of potential working fluids that fulfil the requisites of the present study (Table 4), octafluoropropane (C₃F₈) appears to be uniquely suited for use with FP collectors due to their low output temperatures (<85 °C). In this case the total efficiency is very low (3.31%, Table 6) but the maximum temperature of the ORC cycle and that required from the solar collector is

Table 6
Results for the optimisation using FPC collectors

Working fluid		η_{total} (%)	T_1 (°C)	η_{ORC} (%)	η_{FPC} (%)
Octafluoropropane	R-218	3.31	87.34	7.81	42.39
0.50 R-125	R410A	2.01	82.7	4.48	44.96
0.05 R-32					
0.52 R-134a	R407C	2.89	71.8	5.68	50.80
0.25 R-125					
0.23 R-32					
Propane	R-290	2.36	68.2	4.48	52.67

quite moderate. The temperature T_1 indicated in Table 8 is the temperature at the turbine inlet that maximises the overall efficiency.

Other available fluids could be used based on their individual properties, such as propane, but its overall efficiency is considerably lower than that of octafluoropropane. The optimal temperature of propane is lower but it is not compensated by a corresponding increase in solar field efficiency.

There are other fluids widely used as refrigerants that could be also applied for the FPC operating temperature range, R410A and R407c. The latter offers a performance somewhat less acceptable than octafluoropropane.

4.2. Evacuated tube collectors

Some of the working fluids included in the first selection of fluids (Table 3) could be used in an ORC cycle driven by an ETC solar plant (outlet temperature below 130–150 °C). These fluids and their results are shown in Table 7.

The 1,1,1,2,2-pentafluoropropane (R-245) is the fluid offering the best overall efficiency although the associated solar plant exhibits the lowest efficiency. An isomer of this fluid, 1,1,1,3,3-pentafluoropropane (R-245fa), is used by UTC technologies in their commercialised ORC system [27].

4.3. Compact parabolic trough collectors

The results obtained using compact PTC collectors and selected working fluids are shown in Table 8. There is a group of fluids with the highest overall efficiency, around 18%: MM, *n*-heptane, cyclohexane and toluene. All of them work at condensing pressures below atmospheric.

Table 7
Results for the optimisation using ETC collectors

Working fluid		η_{total} (%)	T_1 (°C)	η_{ORC} (%)	η_{ETC} (%)
Octafluoropropane	R-218	4.52	113.7	7.97	56.67
1,1,1,2,3,3,3-heptafluoropropane	R-227	4.76	89.9	8.00	59.42
1,1,1,2,2-pentafluoropropane	R-245	7.39	120.94	13.24	55.77
1,1,2,2-tetrafluoroethane	R-134	6.91	114.1	12.21	56.62
Octafluorocyclobutane	R-C318	7.36	120.9	13.24	55.77
Decafluorobutane	R-31(1B)	7.37	120.9	13.21	55.77
Propylene	R-1270	4.03	86.4	6.74	59.81
1,1,1,2-tetrafluoroethane	R-134a	3.67	75.4	6.03	60.97

Table 8
Results for the optimisation using compact PTC collectors (Solitem PTC 1000)

Working fluid		η_{total} (%)	T_1 (°C)	η_{ORC} (%)	η_{PTC} (%)
Octafluoropropane	R-218	4.99	75.7	6.78	73.49
1,1,1,2,3,3,3-heptafluoropropane	R-227	8.30	104.6	11.47	72.37
1,1,1,2,2-pentafluoropropane	R-245	8.23	103.7	11.37	72.41
1,1,2,2-tetrafluoroethane	R-134a	9.52	121.9	13.30	71.57
Octafluorocyclobutane	R-C318	11.46	146.3	14.90	70.28
Decafluorobutane	R-31(1B)	10.27	127.3	14.41	71.30
Isobutane	R-600A	11.70	150.0	16.69	70.07
1,1,1,2,3,3-hexafluoropropane	R-236EA	12.18	179.1	17.84	68.25
Bis-difluoromethyl-ether	R-E134	10.53	143.7	14.95	70.43
<i>N</i> -butane	R-600	11.72	170.0	17.02	68.85
Ethyl-amine	R-631	11.93	163.7	17.23	69.25
2-difluoromethoxy-1,1,1-trifluoro	R-E245	14.47	188.2	21.40	67.63
Methyl-formate	R-611	13.55	177.3	19.82	68.37
Isopentane (2-methyl-butane)	–	17.22	289.7	29.26	58.86
Diethyl-ether	R-610	14.74	200.0	22.07	66.78
<i>N</i> -pentane	–	15.37	213.7	23.37	65.74
Dibromodifluoromethane	R-12B2	15.54	233.7	24.23	64.11
1,2-dibromotetrafluoroethane	R-114B2	13.84	208.2	20.92	66.16
<i>N</i> -hexane	–	16.74	233.7	26.12	64.11
Hexamethyldisiloxane	MM	17.98	245.5	28.51	63.09
<i>N</i> -heptane	–	18.50	263.7	30.11	61.43
Cyclohexane	–	18.21	278.9	30.38	59.95
Octamethyltrisiloxane	MDM	15.68	307.3	27.50	57.01
<i>N</i> -octane	–	17.18	291.9	29.29	58.64
Toluene	–	17.84	313.7	31.68	56.31
Decamethyltetrasiloxane	MD2M	13.45	336.4	25.04	53.72
Ethylbenzene	–	16.85	341.9	31.75	53.08
<i>N</i> -propylbenzene	–	15.75	360.0	30.97	50.86
<i>N</i> -butylbenzene	–	14.44	388.2	30.59	47.21
Tribromomethane	R-20B3	13.84	400.9	30.43	45.47

The second best group has an efficiency around 15%. The best fluid is Isopentane with an efficiency a bit higher than 17% although the optimum operation temperature for the ORC cycle is quite high (290 °C). The second best choice could be *n*-pentane that exhibits a lower efficiency (15.4%) but at a moderately high-temperature (214 °C).

4.4. High temperature parabolic trough collectors

These types of collectors offer a high efficiency for high temperature working fluids and are intended to be used in

Table 9
Results for the optimisation using high temperature PTC collectors (Eurotrough)

Working fluid	η_{total} (%)	T_1 (°C)	η_{ORC} (%)	η_{PTC} (%)
Dibromomethane	10.49	370.0	15.69	66.87
Ethylbenzene	4.39	384.6	6.61	66.34
<i>N</i> -propylbenzene	21.44	377.3	32.19	66.61
Tribromomethane	9.92	432.8	45.39	64.45

Table 10
Performance of the solar ORC–RO system for brackish water desalination

Working fluid	Collector	w_{cons} (kW/m ³ /day)	T_1 (°C)	η_{ORC} (%)	$m_{\text{desal}}/m_{\text{ORC}}$
Octafluoropropane	FPC	0.117	87.34	7.81	2.38
Pentafluoropropane (R-245)	ETC	0.117	120.94	13.24	7.05
Isopentane	Compact PTC	0.117	289.73	29.26	48.72
<i>N</i> -propylbenzene	High-temp PTC	0.117	377.34	32.19	55.87

thermoelectric solar plants. They are evaluated here for solar ORC desalination. As shown in Table 9 the solar efficiency is comparable to the compact PTC collectors but function at temperatures 150 °C higher. With the exception of *n*-propylbenzene, all the other fluids in this case do not need to use a regenerator, but they offer a lower performance than *n*-propylbenzene.

4.5. Coupling with the RO system

In the previous sections the results for the integrated optimisation of the ORC and thermal solar plant were presented for each type of solar collector. In this section, other performance data are given which is specifically related to the RO subsystem which interacts with the ORC solar system.

Tables 10 and 11 present the results for the desalination of brackish water and seawater for the selected ORC working fluids and their performance. The results shown are calculated assuming 7 h/day of plant operation. The ORC

Table 11
Performance of the solar ORC–RO system for seawater desalination

Working fluid	Collector	w_{cons} (kW/m ³ /day)	T_1 (°C)	η_{ORC} (%)	$m_{\text{desal}}/m_{\text{ORC}}$
Octafluoropropane	FPC	0.415	87.344	7.81	0.66
Pentafluoropropane (R-245)	ETC	0.415	120.94	13.24	2.07
Isopentane	Compact PTC	0.415	259.77	27.61	13.88
N-propylbenzene	High-temp PTC	0.415	378.44	32.19	16.52

power capacity required per m³ of desalted water is almost four times higher in the case of seawater. Also, the amount of desalted water is considerably higher in the case of brackish water. With respect to the solar technologies, the amount of desalted water per kg of circulating working fluid in the ORC cycle is by far the most favourable using the PTC technology.

5. Case studies

Two case studies in two different locations have been performed to illustrate the applicability of the solar ORC–RO system and to calculate the required size of the thermal solar plant. The two locations are Almería and Barcelona, and can be considered representative of two different levels of solar radiation characteristic of the Mediterranean area in Spain. In these case studies the area of the solar field collectors is calculated for both locations, considering both brackish and seawater desalting applications.

5.1. Description

TRNSYS can model the weather data during any period from a few seconds up to one year. In this case simulations

are performed for a complete year, from 0 to 8760 h. The result is the average desalinated water flow rate per year. The criterion fixed to calculate the solar field size is production of about 15 m³/day with the different types of collectors. Fig. 4 shows a graphic example of these results. In the case of FPC and ETC collectors the heat transfer fluid used in the solar field is water, while for PTC collectors the fluid used is the thermal oil Therminol 72 (specific heat: 2.528 kJ/kg K, density: 753 kg/m³ at 380 °C). No thermal energy back-up is used for the studied cases. It is supposed that the desalted water storage will be enough to handle the correct match between production and consumption of desalted water.

In all the simulated cases the data come from the available hourly TMY files included in the TRNSYS 16 software. These data files distributed with TRNSYS 16 were generated using default options in Meteororm V 5.0.13 and meteorological data from Almeria and Barcelona.

With regard to the solar field arrangement, in all the simulated cases for FPC, ETC-CPC thermal collectors and photovoltaic panels was considered a true south orientation (Azimuth = 0°) and a tilt angle of 35°. The reason for that arrangement is that it is the best option to achieve the maximum annual solar irradiation in the Iberian Peninsula

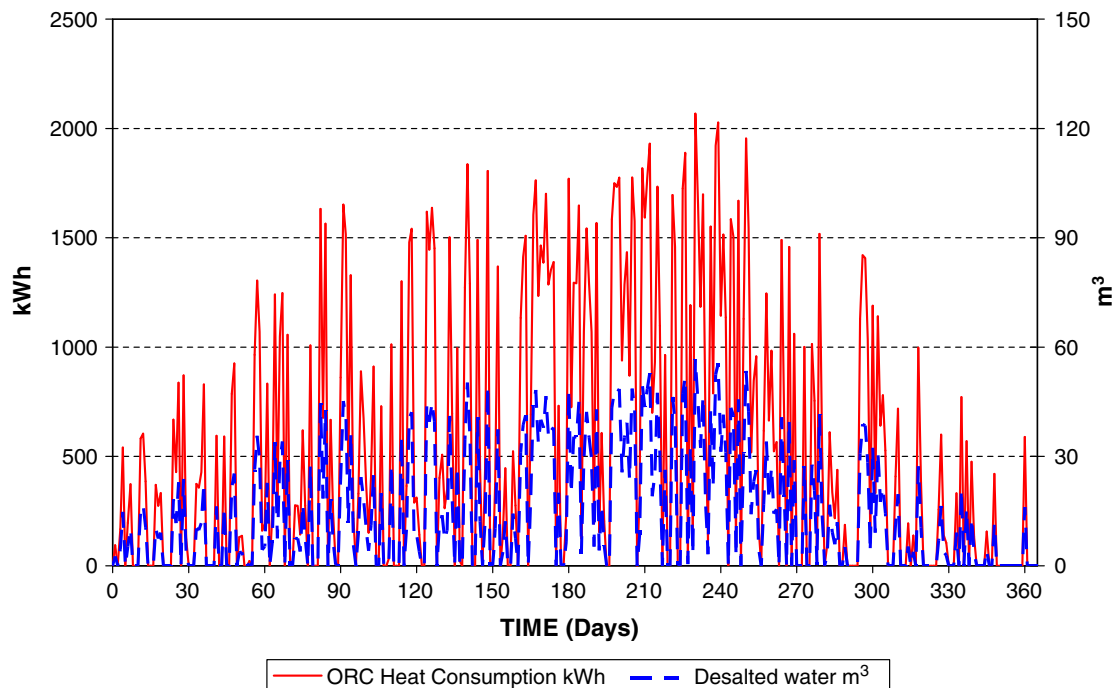


Fig. 4. Heat supplied to the ORC system and desalted water flow rate. Case of Barcelona using FP solar collectors with a size of 258 m².

latitudes (41.38° Barcelona, 36.83° Almeria) and then, the maximum annual output useful energy and desalted water production.

In the case of PTC collectors was considered a tracking mode which handles the general case of a surface rotating about a single axis that is always parallel to the surface. In all the simulated cases with these collectors, the orientation and slope of this tracking axis was North–South and 0°, respectively.

5.2. Design and technical performance

The optimum area of the solar collectors and the collector thermal fluid flow rate is calculated using the solar plant TRNSYS model coupled with the ORC–RO Aspen plus model. The results for the Barcelona and Almería locations are presented in Tables 12 and 13. TRNSYS calculates the desalted water flow rate using the Aspen plus simulation results. This way the quantity of desalted water per unit of thermal energy provided to the ORC is known, or its equivalent, which is the thermal energy required from the solar plant.

In the TRNSYS model it was assumed that if the solar plant thermal energy produced is below 25% of the calculated thermal energy for the targeted desalted water flow

rate, the production of desalted water is zero. This restriction was taken as a reasonable value for the minimum load of the turbine in the ORC. The pressure in the RO system will not change as the power output of the turbine decreases. If the solar thermal energy decreases in order to keep constant the operating pressure for the RO membrane to operate correctly the flowrate of the sea or brackish water will have to be reduced by the control system.

Table 14 shows the equivalent power required using a photovoltaic system to provide the power required for the high-pressure RO pump.

5.3. Cost analysis

This section gives a preliminary estimation of the capital cost required at each location for the proposed solar ORC–RO desalination system. This economic analysis will be used to select the best solar collector technology and compare it with a photovoltaic system to electrically drive the RO system at both locations, and with two different levels of salinity.

The capital cost is a function of the solar field area and the RO and ORC capacity. The cost estimation is calculated for a production of 15 m³/day of desalted water. The specific investment cost per desalted water per year c_{tot}

Table 12
Main design results for the Barcelona case

	FPC		ETC		Compact PTC		High-temp PTC	
	Brackish water	Seawater	Brackish water	Seawater	Brackish water	Seawater	Brackish water	Seawater
Solar field results								
A (m ²)	258	720	107	359	88	200	69	138
Number of solar collectors	112	312	98	330	44	100	1	2
Desalted water production								
m_{desal} (m ³ /day)	15	15	15	15	15	15	34	23
Nominal operating conditions								
m_{ORC} (kg/s)	1.68	4	0.567	1.28	0.0821	0.1905	0.0716	0.1601
m_{solar} (kg/s)	0.556	1.67	0.75	0.833	0.833	0.833	0.75	0.75
Q_{ORC} (kW)	146	348	95	215	41	93	38	85

Table 13
Main design results for the Almería case

	FPC		ETC		Compact PTC		High-temp PTC	
	Brackish water	Seawater	Brackish water	Seawater	Brackish water	Seawater	Brackish water	Seawater
Solar field results								
A (m ²)	157	517	87	283	68	128	69	69
Number of solar collectors	68	224	80	260	34	64	1	1
Desalted water production								
m_{desal} (m ³ /day)	15	15	15	15	15	15	57	18
Nominal operating conditions								
m_{ORC} (kg/s)	1.68	4	0.567	1.28	0.0821	0.1905	0.0716	0.1601
m_{solar} (kg/s)	0.556	1.67	0.75	0.833	0.833	0.833	0.75	0.75
Q_{ORC} (kW)	146	348	95	215	41	93	38	85

Table 14
Main design results for an equivalent photovoltaic based system

	Barcelona		Almería	
	Brackish water	Seawater	Brackish water	Seawater
Modules in series	10	10	10	10
Modules in parallel	8	28	7	24
W_{PV} (kW)	12	28	12	28
Area (m ²)	134	469	117	402
W_{Peak} (kW)	16	56	14	48

(€/m³y) is calculated as shown in Eq. (6). The capital recovery factor (f) has been taken as 0.15 y⁻¹.

$$c_{tot} = \frac{C_{ORC} + C_{solar} + C_{RO}}{m_{desal}} \cdot f \quad (6)$$

where

$$C_{solar} = IC_{solar} + OM_{solar} \quad (7)$$

$$C_{RO} = IC_{RO} + OM_{RO} \quad (8)$$

There is not much precise information about the current capital cost of commercialised ORC. Bronicki [28] mentions a cost ranging from 1150 to 2200 US\$/kW for geothermal applications depending on the quality of the geothermal resource for a plant of more than 30 MW. Verloop [29] gives a cost of 1600 US\$/kW for a 175 kW plant that is under development. Invernizi et al. [30] consider a specific cost characteristic of ORC plants of 2.5–3 k€/kW in the range of 50–100 kW without providing the source of this data. The cost for a commercial ORC module of

Table 15
Unitary costs for the main process equipment

RO – brackish water	(€/m ³ /day)	600
RO – sea water	(€/m ³ /day)	1600
ORC	(€/kW)	2000
ET collectors	(€/m ²)	570
FP collectors	(€/m ²)	235
PT SOLITEM collectors	(€/m ²)	400
PT EUROTROUGH collectors	(€/m ²)	400
Photovoltaic collectors	(€/k Wp)	8000

Table 16
Specific annual cost in €/m³ of the plant for both geographic locations

Location	Raw water	ORC–RO-FPC	ORC–RO-ETC	ORC–RO-PTC solitem	ORC–RO-PTC eurotrough	RO-PV
Almería	Brackish	2.86	2.36	2.03	2.30	3.80
	Seawater	7.99	6.28	4.32	4.90	12.83
Barcelona	Brackish	3.31	3.29	2.36	2.33	4.31
	Seawater	9.54	7.87	5.50	4.66	14.85

Table 17
Cost distribution in % between the plant main subsystems in Barcelona

	FP collector		ET collector		PTC Solitem		PTC Eurotrough		PV	
	Brackish	Seawater	Brackish	Seawater	Brackish	Seawater	Brackish	Seawater	Brackish	Seawater
RO	7.9	8.8	7.8	7.2	11.0	12.5	23.1	18.5	6.0	4.6
ORC	20.0	19.5	19.9	16.1	27.9	27.9	28.3	32.9	–	–
Solar field	72.1	71.7	72.3	76.7	61.1	59.6	48.6	48.5	94.0	95.4

1 MW_e used for biomass applications currently is about 1600 €/kW_e. According to this information in the present study, an average value for the cost of the ORC subsystem has been estimated at 2000 €/kW.

With respect to the solar collector field, the capital cost for the FP and ET collectors has been taken from Henning [31]. For PT collectors the data is harder to find for collectors used in applications other than large thermo solar power plants. The cost reported in Poship [32] has been used. In case of photovoltaic energy, data have been extracted from Falk et al. [33]. The cost of the solar plant has been calculated as the cost of the solar collector field plus another 30% to account for other solar plant components.

The capital cost for the RO desalination plant used in this study is based on two references that included investment data for small size RO brackish and sea water plants [34,13]. The unit costs used for all the solar ORC–RO subsystems are given in Table 15. The operation and maintenance costs for the solar plant for the case of FPC and ETC collectors has been estimated to be 10% of the investment cost and 15% in the case of PTC collectors. For the RO, the operation and maintenance costs have been considered to be a 5% of their investment cost.

According to the techno-economic results obtained in both locations (Table 16), PTC is the best option to minimise costs. Results show that PTC Eurotrough using *n*-propylbenzene as the ORC working fluid is the best choice for Barcelona and PTC Solitem with isopentane ORC fluid the best option for Almería. Thus in the location with the highest solar radiation, less efficient but more compact PTC collectors can be selected.

For solar power cycles, McMahan et al. [35] stated that the typical capital cost break-down is 75% for the solar field and 25% for the power cycle. For the cases studied, Tables 17 and 18 show the cost distribution for all the cases studied for the solar ORC–RO system in Barcelona and Almería. The distribution is similar in both locations, obviously with a slightly lower contribution of the solar plant in the site with the highest solar radiation. The contribution of the ORC is as a maximum around 30% of the total cost.

Table 18
Cost distribution in % between the plant main subsystems in Almería

	FP collector		ET collector		PTC Solitem		PTC Eurotrough		PV	
	Brackish	Seawater	Brackish	Seawater	Brackish	Seawater	Brackish	Seawater	Brackish	Seawater
RO	11.0	11.0	9.1	8.6	12.8	16.0	21.5	44.5	6.8	5.4
ORC	27.8	24.4	23.0	19.2	32.4	35.5	28.9	32.0	–	–
Solar field	61.2	64.6	67.9	72.2	54.9	48.5	49.7	23.6	93.2	94.6

6. Conclusions

A comprehensive list of working fluids has been analysed to optimise the performance of solar organic rankine cycle engines for reverse osmosis desalination using currently available solar thermal collectors. The fluids reviewed were chosen based on the criterion of having a positive slope of the vapour saturation line in the temperature–entropy diagram.

The simulation results of the selected working fluids showed that highest efficiencies were obtained with fluids having the highest critical temperature. The problem with these fluids was that the condensing pressure was lower and consequently their density at the turbine outlet was also low. Thus in practice these fluids require the installation of comparatively more voluminous equipment. There is a group of fluids having about 20% ORC efficiency such as *n*-pentane or isopentane and a vapour density 10 times higher than the group close to the 30% efficiency which would be suitable for the applications studied.

The highest operating temperature of the ORC has been optimised as a compromise between high ORC and solar plant efficiency in order to obtain the highest overall efficiency. The main types of thermal solar collectors available were considered, and the most adequate fluid was selected. Under the considered restrictions for fluids in the case of FPC, the best results were obtained with octafluoropropane. For ETC, the R-245 offers the best overall efficiency among the selected fluids. However, the best results were obtained with PTC collectors. For the compact PTC Solitem collector, the use of isopentane is proposed as a compromise between high efficiency (30% for the ORC and 17% overall) and fluid high density at the lowest cycle pressure. For the PTC Eurotrough, *n*-propilbenzene has the highest ORC and overall efficiency (32% and 21%, respectively).

Two case studies were performed to illustrate the applicability of the system in Almería and Barcelona. These locations were considered representative of two different levels of solar radiation characteristic of the Mediterranean area of Spain. In the case studies the area of the solar field collectors was calculated, considering both brackish and sea water desalting applications for a capacity of 15 m³/day. The net mechanical power required from the ORC for the brackish water case was 11.72 kW and 27.82 kW for the seawater case. According to the preliminary techno-economic results obtained for these two locations, the most adequate thermal solar technology was represented by the PTC collectors. Specifically, PTC Eurotrough collectors using

n-propilbenzene as the ORC working fluid was the best choice for Barcelona and PTC Solitem collectors with isopentane ORC fluid were the best option for Almería. Thus in the location with the highest solar radiation, less efficient but more compact PTC collectors can be selected.

The use of a photovoltaic system to generate electricity to drive the RO desalination system has a higher cost than the optimised solar ORC–RO system especially in comparison with the best solar thermal technology, the PTC system. Thus, according to the current techno-economic framework, the PTC system is the best choice.

The solar organic rankine cycle engine system for RO desalination using currently available solar thermal collectors is potentially attractive for remote areas without, or with very high cost access to the public electricity grid in concurrence with other renewable energy technologies for desalination.

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